ADAPTIVE BANDWIDTH MANAGEMENT AND QOS PROVISIONING IN LARGE SCALE AD HOC NETWORKS

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ABSTRACT

Quality of service provisioning in wireless ad hoc networks plays an integral part in determining the success of network-centric warfare as envisioned in future military operations. It requires good scalability of the QoS architecture since ad hoc networks in the battlefield tend to be large. Previous work attacking QoS in ad hoc networks seldom considers the scalability issues. In this paper, we propose a scalable QoS architecture for such networks. Our scheme draws upon the positive aspects of both IntServ and DiffServ, and extends upon the scalable LANMAR routing protocol to support QoS. The scheme is also capable of incorporating mobile backbone networks (MBNs) to further improve the scalability. Simulation results show that our proposed QoS architecture can achieve good scalability in terms of large network size and mobility.

I. INTRODUCTION

Quality of service provisioning in wireless ad hoc networks plays an integral part in determining the success of network-centric warfare as envisioned in future military operations. Unlike in the wired networks where bandwidth is usually abundant, bandwidth of the wireless ad hoc nets is always scarce. Providing QoS guarantee, or at the very least some kind of differentiated services, is necessary to help deliver mission-critical data (e.g. calls of generals). Thus, QoS is important to the battlefield deployment of wireless ad hoc networks. QoS provisioning in an ad hoc mobile network is not a new concept. The problem is remarkably more difficult than in wired networks, but it has been attacked before, proposing several schemes such as the SWAN model [1]. However, scalable QoS provisioning in large-scale ad hoc networks draws little attention. It poses additional difficulties that have not been addressed. In this paper, we propose a scalable QoS architecture targeting networks of up to thousands of nodes (while existing schemes generally apply to single hop systems or small size networks). Our environment includes heterogeneous nodes with different radio capabilities. These features render the QoS problem unique, and require a novel approach.

Our QoS architecture draws upon the positive aspects of both IntServ and DiffServ [2]. In our scheme, we measure the available bandwidth and perform call admission control (CAC) based on the available bandwidth information. However, we do not reserve bandwidth along the path as IntServ does. Thus, there is no need to maintain per flow state information at the intermediate nodes. Since the network size is big, traditional end-to-end probing-based admission control cannot fulfill the delay requirement. To circumvent this problem, we adopt the QoS routing to propagate bandwidth information throughout the network. The scalability of the QoS routing is supported by the Ad Hoc Landmark Routing (LANMAR) which has been shown to scale to thousands of nodes [4]. However, CAC based on available bandwidth can only prevent network overload without mobility. Under mobility, the topology may change after a flow is admitted, resulting in changes of traffic distribution in the network. Thus, congestion may still occur under mobility even though there is enough bandwidth at the time of flow admission. In order to prevent performance degradation due to mobility-triggered congestion, we developed an additional congestion control scheme. Once congestion occurs, best effort traffic must then reduce its rate to relieve congestion. Some real-time flows may also be suspended under heavy congestion. All these schemes together make the proposed QoS architecture scalable to large network size and mobility.

The rest of the paper is organized as following. We briefly review some related work in section II and give an overview of the proposed QoS architecture in section III. Four major components of the QoS architecture are then explained in detail in section IV, V, VI, and VII respectively. Performance evaluation results are presented in section VIII and we conclude the paper in section IX.

II. RELATED WORK

QoS provisioning in mobile ad hoc networks is not new. Recently, several schemes have been proposed, such as SWAN [1], INSIGNIA [6], and CEDAR [12]. Among them, the SWAN model shares many design concepts and features with our scheme. The SWAN model uses ”probing” to obtain the minimal available bandwidth on the path, assuming the routing protocol has found a valid path. The admission control at the source node is then based on the probed bandwidth information. SWAN also proposes to use rate control to manage the best-effort traffic for responding to network congestion. It also marks the ECN bits of packets to indicating network congestion. However, our proposed scheme also has significant differences compared to the SWAN model.

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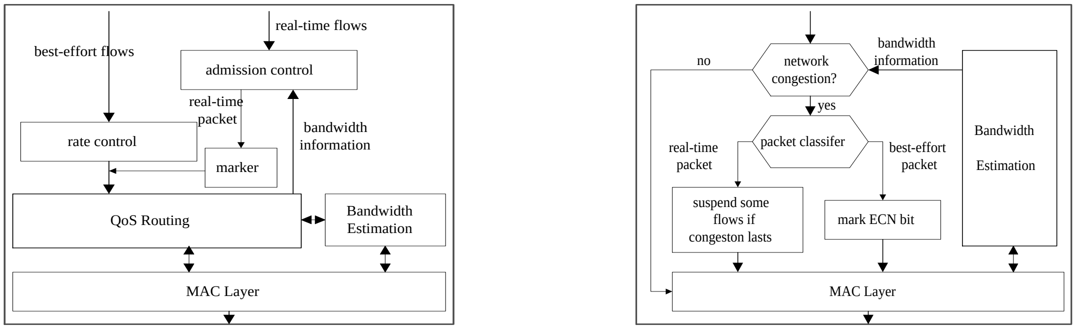


Fig. 1. *Overview of the proposed QoS architecture.* Left: Actions performed at the source nodes. Right: Actions performed at intermediate nodes.

Our scheme provides good scalability by utilizing the LANMAR routing protocol and the MBN hierarchical structure. SWAN doesn't assume any specific underlying routing protocol. Our scheme instead extends the LANMAR routing to propagate bandwidth information. By doing so, we gain many important advantages. For example, this approach reduces the admission delay since most information needed for admission control is now available at each node. In contrast, the SWAN model uses "probing" to get the bandwidth information on-demand and thus the call admission delay experienced will be quite large. The INSIGNIA model and the CEDAR model are mostly IntServ-type QoS schemes, which are quite different from our DiffServ model. We believe that our DiffServ approach will work better and more practical in the mobile wireless environment.

In our proposed QoS architecture, we assume the standard IEEE 802.11 MAC, which makes our protocol very practical. However, IEEE 802.11 MAC does not distinguish between real-time and best-effort traffic. There are research efforts where the IEEE 802.11 is modified to support real-time traffic. One such protocol is proposed in [11]. Although our scheme doesn't require support from such kind of enhanced MAC protocols, there is no restriction on our scheme to utilize such protocols.

III. Overview of the Architecture

An overview of the proposed QoS architecture is illustrated in Fig. 1. The left hand diagram shows the actions performed at the source nodes of flows. The right hand diagram depicts the actions at intermediate nodes. As in Fig. 1 (left side), real-time flows first enter the admission control component. Once admitted, its packets will be marked as real-time packets and given to the routing protocol for delivery. In contrast, best-effort traffic bypasses admission control; they are directly injected into the network. However, to guarantee the QoS requirements of existing, admitted real-time flows, the best-effort traffic is rate-controlled to make sure they only use free bandwidth left by real-time traffic. The task of the intermediate nodes is quite simple. As shown in the right side of Fig. 1, the intermediate nodes need only to detect network congestion and mark the ECN bits of the packets experiencing congestion.

The proposed QoS architecture has four basic components, namely adaptive bandwidth management, scalable QoS routing, call admission control and congestion control. The adaptive bandwidth management measures the available bandwidth at each node in real-time. This bandwidth information is then propagated pro-actively or retrieved on demand by the scalable QoS routing. The source nodes (known as ingress routers in the DiffServ model, perform call admission control for real-time flows based on the bandwidth information provided by the QoS routing. The congestion control part is unique to mobile ad hoc networks. In a MANET, even though admission control is performed to guarantee enough available bandwidth before accepting any real-time flow, the network can still experience congestion due to mobility or connectivity changes. Thus, the fourth component, congestion control, is extremely important to our QoS architecture. It monitors the network bandwidth utilization continuously and detects network congestion in advance with the help of the adaptive bandwidth management component. AIMD (additive increase, multiplicative decrease) rate control is then used to regulate best-effort traffic and ensure that best-effort traffic coexist well with real-time traffic.

It has been proven that the per node throughput of an ad hoc network decreases rapidly when the network size is increased [5]. Thus, a "flat" large scale ad hoc network has an inherent scalability limitation in terms of achievable network capacity. To improve scalability, in this paper, we also propose to incorporate our QoS architecture with physical, hierarchical ad hoc networks, known as the mobile backbone network (MBN). The MBN structure has been proposed and studied in the literature. In this paper, we adopt the MBN structure presented in [14].

IV. Adaptive Bandwidth Management

We use bandwidth information as the metric of choice for QoS provisioning. We will examine other metrics, such as end-to-end packet delay and packet loss rate, in future research. In our QoS architecture, each node will continuously estimate its available bandwidth. The bandwidth information will then be used for QoS capable routing protocols to provide support to admission control. Also, in our scheme, a node detects the network congestion around itself by monitoring the channel utilization ratio.

A. Real Time Bandwidth Measurement

Accurate estimation of a node's bandwidth utilization is difficult in a multihop packet radio network. Unlike the wired point-to-point infrastructure where bandwidth usage can simply be calculated by determining the transmission frequency of a node, the same is not true in the wireless environment. This is because the wireless medium of a node is shared among neighboring nodes. Thus, we must not only take into account the transmissions

of the node, but also consider the transmissions of all the node's neighbors in determining a node's effective available bandwidth capacity.

In packet radio networks, MAC protocols play an important role in bandwidth estimation. In previous studies, TDMA- and CDMA-like MAC schemes were used since slots can be reserved in such schemes [7]. These are reasonable MAC assumptions in single hop wireless networks. However, they are not acceptable in multi-hop ad hoc networks where the IEEE 802.11 MAC protocol is widely used. IEEE 802.11's contention access scheme is random access based rather than slotted. Therefore, the available bandwidth at a node cannot be decided locally. Neighbor information also needs to be considered.

We propose to compute the available bandwidth based on the channel status of the radio to determine the busy and idle periods of the share wireless media. By examining the channel usage of a node, we are able to take into account the activities of both the node itself and its surrounding neighbors and therefore obtain a good approximation of the bandwidth usage. The channel utilization ratio is defined as the fraction of time within which a node is sensing the channel as being utilized. Generally speaking, an 802.11 wireless radio has four states; (1) Busy state (transmitting or receiving packets), (2) Carrier sensing channel busy (some other nodes within its neighborhood are transmitting packets), (3) Virtual carrier sensing busy (deferral to RTS or CTS packets), and (4) idle state (not in any of the above states). Among the four states, the states (1), (2) and (3) can be treated as busy state and (4) as the idle state. Each node will constantly monitor the channel state changes (from busy to idle or from idle to busy) and record the time period that the radio is in each state. For each time period T, we then calculate the channel utilization ratio as $R = \frac{channel-busy-period}{T}$. To smooth the channel utilization estimation, we define a smoothing constant $\alpha \in [0, 1]$. Suppose the last channel utilization ratio is R_{t-1} and the channel utilization ratio measured in the current sampling time window is R. Then, the current channel utilization ratio is given as $R_t = \alpha R_{t-1} + (1 - \alpha)R$. The channel utilization rate R_t is bounded between 0 and 1. After correctly estimating the channel utilization at time t, we then are able to calculate the available bandwidth of a node at time t as $BW_t = W(1 - R_t)$. Here, W is the raw channel bandwidth (2Mbps for a standard IEEE 802.11 radio).

B. Soft Bandwidth Reservation

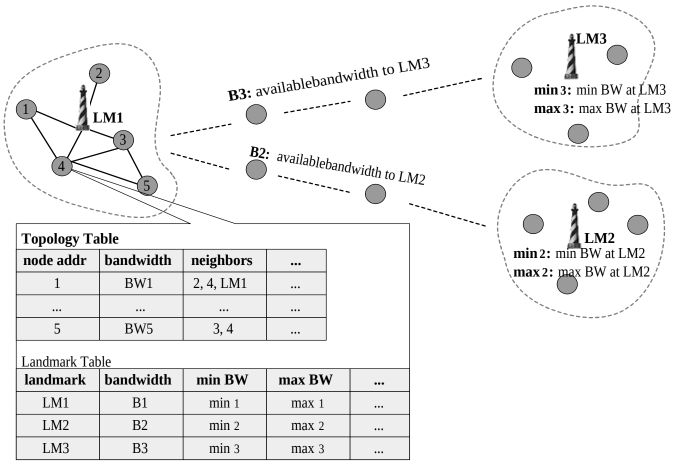
In the military environment, qualify of service guarantees must be stringent. However, hard bandwidth reservation may not be practical as it is extremely difficult to reserve bandwidth in a mobile network. Furthermore, bandwidth reservation that follows the IntServ approach is not scalable as per flow information needs to be maintained. In our scheme, we propose to use a soft, or implicit, bandwidth reservation where each node in the network will periodically calculate its own available bandwidth, based on the bandwidth measurement technique discussed in the previous subsection. The available bandwidth calculation will be used by our call admission control component to determine if flows can be admitted for a particular service class. Once a flow is admitted and starts sending data traffic, the bandwidth resource occupied by the flow will be automatically taken into consideration during the periodic available bandwidth measurement intervals. Therefore, resource reservation is done implicitly without the need to keep track of per flow information; only per class information is needed.

V. Scalable QoS Routing

After correctly measuring the available bandwidth at each node, we then want to extend the ad hoc routing protocol to include bandwidth information. Ad hoc routing protocols can be generally divided into two categories, namely proactive routing and on-demand routing. In this QoS work, we are targeting large-scale ad hoc networks. Thus, scalability of the routing protocol is one of the most important considerations. It is well known that a ”flat” proactive routing protocol cannot scale well in the mobile environment. On-demand routing shows better scalability than the traditional proactive routing protocols. However, on-demand protocols still cannot scale to large networks (e.g., thousands of nodes) under mobility. To achieve good scalability, routing protocols with some form of hierarchical structure are proposed. One such ad hoc routing protocol that scales to networks with thousands of nodes is the Landmark Ad Hoc Routing (LANMAR) [4]. We select LANMAR as the underlying routing protocol for supporting our QoS architecture. However, the QoS architecture is not limited to any specific routing protocol. Since on-demand routing shows good performance in small scale (e.g., up to 100 nodes) ad hoc networks, we also investigate our proposed QoS architecture on top of the AODV [9] routing protocol. However, due to page limitations, we will not present AODV results in this paper. In this section, we explain in detail how we extend the LANMAR routing protocol to propagate bandwidth information.

LANMAR routing consists of two mostly independent routing protocols, the local scoped routing and the landmark distance vector routing. The local routing protocol can be any type of ”flat” ad hoc routing protocol. Here, we use the scoped Fisheye link state routing protocol [8]. Fisheye's QoS extension is quite easy and very similar to Q-OSPF. Since Q-OSPF is widely studied in the wired Internet, we do not describe the details of Fisheye's QoS extension. With this extension, a node can compute the available bandwidth from itself to each other node within its local scope. The routing across groups in the LANMAR protocol is provided by the propagation of landmark distance vectors. LANMAR distance vectors provide the summary of routing information to landmark groups (more precisely, to the representatives of groups, the landmarks) rather than the precise routing information to individual nodes. To include the bandwidth information, we modify the Landmark Update as follows.

1) Each landmark computes the minimal and maximal available bandwidth (min_{BW} and max_{BW}) to any other node within its landmark group. This can be done with the help of the local scoped QoS routing.
2) The landmark distance vectors carry the min_{BW} and max_{BW} calculated by each landmark and are then propagated throughout the network.
3) The distance vector routing of the landmark information propagation also needs QoS extension. Each distance vector then adds one more QoS field to record the minimal bandwidth to the corresponding landmark. When a node



node addr	bandwidth	neighbors	...
1	BW1	2, 4, LM1	...
...	...	...	...
5	BW5	3, 4	...

landmark	bandwidth	min BW	max BW	...
LM1	B1	min 1	max 1	...
LM2	B2	min 2	max 2	...
LM3	B3	min 3	max 3	...

Fig. 2. Illustration of QoS Extended LANMAR Routing.

broadcasts the landmark distance vectors, it will compare its available bandwidth with the minimal bandwidth fields in the vectors. If its available bandwidth is smaller, then the minimal bandwidth fields will be updated with its available bandwidth. This is exactly a QoS distance vector routing.

With the above extensions, each node will now have 1) the exact available bandwidth information to all other nodes within its scope (by the virtual of the local QoS routing algorithm), 2) the exact available bandwidth information to all landmarks, and 3) the minimal and maximal bandwidth of each landmark to any other node within its landmark group.

The QoS extended LANMAR (Q-LANMAR) routing is illustrated in Fig. 2. Three landmark groups are explicitly shown in the figure. We also show the topology table (the table maintained by the Fisheye local routing protocol) and the Landmark routing table of node 4. With the QoS extension of the local routing protocol, we can see that node 4 maintains accurate available bandwidth information to all nodes within its landmark group. However, it does not have accurate bandwidth information to remote nodes in other groups. Such bandwidth information is summarized as available bandwidth information to all landmarks, which is given as B_1, B_2, and B_3 in the landmark table of node 4. In addition to bandwidth information to landmarks, the minimal and maximal available bandwidth of one landmark to any node within its group is also propagated. Such information gives approximate understanding of the internal bandwidth usage in each landmark group, which will help during the call admission process described in next section. The minimal and maximal bandwidth information can be found in the min_{BW} and max_{BW} fields of node 4's landmark table.

VI. Call Admission Control

With the support from the underlying QoS routing, the source node can then decide whether to admit a new real-time flow. This is usually referred to as call admission control (CAC). Since QoS-LANMAR is basically a proactive routing protocol, the bandwidth information is already available at each node. When a new request with certain bandwidth requirement comes, the source will perform admission control following the procedure described below.

- The source node first consults the local routing table. If the destination is within the local scope and the available bandwidth is enough, then the flow is accepted. If the destination is within scope, but bandwidth is not enough, then, reject the flow.
- If the destination is not within the local scope, the source node then consults the landmark routing table. It first examines whether it has enough bandwidth to the corresponding landmark node of the destination. If not enough, the flow is rejected.
- If bandwidth to the landmark node is enough, the source node then has to further check the minimal and maximal bandwidth propagated by that landmark. If the requested bandwidth is smaller than min_{BW}, the flow can be admitted. If the requested bandwidth is larger than max_{BW}, the flow is rejected.
- If, however, the requested bandwidth falls between min_{BW} and max_{BW}, the bandwidth information in the landmark routing table is not enough to make an admission decision. A probing packet is then sent by the source node to the corresponding landmark to collect the exact available bandwidth to the destination node. After getting the reply back, if the available bandwidth can meet the requirement, then accept the flow. Otherwise, the flow is rejected.

VII. Congestion Control

In mobile ad hoc networks, call admission control at source nodes alone cannot guarantee QoS since the topology may change after flows are admitted. Network congestion can still occur frequently under mobility. Thus, congestion control is needed to provide QoS in such situations. When network congestion occurs, we would like best-effort traffic to first reduce their transmission rate to give bandwidth to real-time flows.

A. Network Congestion Detection

To exercise congestion control, we need to first detect network congestion. Congestion is straightforward to detect in wired networks. Usually, when congestion occurs, the queue at the bottleneck link will build up, or even overflow, causing packet drops. However, in multi-hop wireless networks, correctly detecting congestion of a neighborhood is difficult. The queue length is no longer a valid indication of congestion. The MAC layer usually retries a transmission for a limited number of times (e.g. default retry time of the IEEE 802.11 DCF is 7) before dropping a packet. Thus, a queue may not have yet build up at the early stage of congestion. In our scheme, we want to detect congestion in a node's neighborhood by monitoring the wireless channel utilization ratio. This information can be provided by the adaptive bandwidth estimation scheme discussed in section IV. We define a threshold value, and when the channel utilization ratio is larger than this threshold, we can assume that this node's neighborhood is entering a congested state.

B. Rated Control of Best Effort Traffic

We propose to apply rate control to best-effort traffic in order to combat congestion. In our scheme, best-effort traffic may use any bandwidth not consumed by real-time flows. However, once a new real-time flow arrives, the rate control scheme forces best

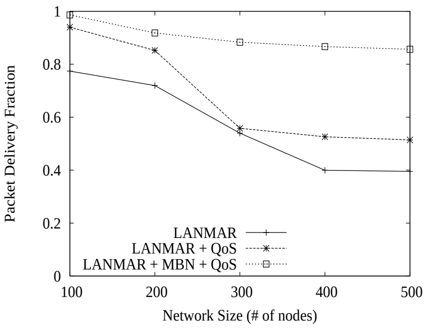


Fig. 3. Delivery fraction vs. network size.

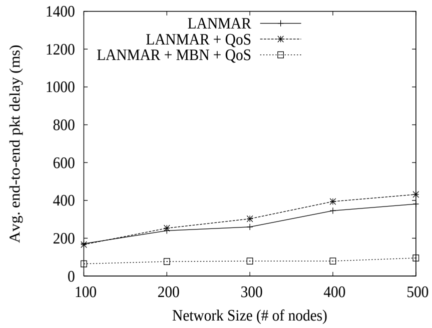


Fig. 4. End-to-end pkt delay vs. network size.

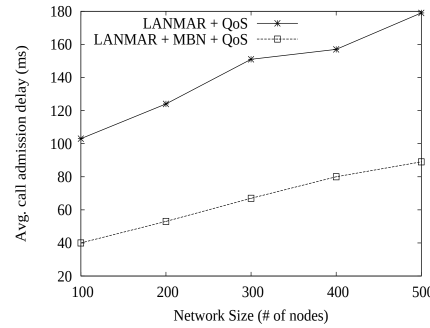


Fig. 5. Call admission delay vs. network size.

effort traffic flows to free the bandwidth for the new real-time flow. The starvation of best effort flows is prevented by reserving a small fraction of the bandwidth to best-effort traffic at all times. The basic idea of our rate control scheme is that all the best-effort traffic start with very low rate and increase the rate when there is no congestion. Once congestion arises, the ECN bits of best-effort traffic will be marked and propagated to the source nodes. The sources will then reduce their rate. Rate control is not new in the literature and many rate control schemes have been proposed. Here we select the simple Additive Increase and Multiplicative Decrease (AIMD) scheme. It is the scheme used in TCP congestion control and has been proved to achieve both efficiency and fairness [3].

VIII. Performance Evaluation

In this section, we evaluate the proposed QoS architecture using simulation. The simulator used is the fast, efficient and scalable (up to thousands of nodes) QualNet simulator [10]. According to [13], QualNet incorporates a very detailed and accurate model of the physical channel and of the IEEE 802.11 MAC layer, which provides a good platform for our performance study. In all our simulations, the channel model is TWO-RAY GROUND. We compare the network performance under heavy real-time traffic with and without applying the proposed QoS architecture. To enhance scalability, we also applied the mobile backbone network (MBN) to our QoS architecture. In all simulations, 25% of the mobile nodes are backbone capable. Dynamic backbone election is then used to elect the backbone nodes to establish the backbone network. The primary metrics considered for performance evaluation are data packet delivery fraction, average data packet end-to-end delay and call admission delay.

A. Scalability with Network Size

In this experiment, we investigate the scalability of the proposed schemes with various network size. The network size (in terms of number of mobile nodes) examined here is from 100 nodes to 500 nodes. For each network size, we keep the same node density at 40 node/km^2, which is achieved by adjusting the field size according to the number of nodes. The group mobility model is applied with mobility speed as high as 10m/s. The IEEE 802.11 MAC is used for both the ground radio and the backbone radio. The transmission range of the ground radio is 376m while that of the backbone radio is 800m. The channel bandwidth is 2Mbps for ground radio and 11Mbps for backbone radio. The real time flows are emulated using Constant Bit Rate (CBR) traffic. For each network size, 10 CBR flows with rates of 160Kbps are used at various starting time. Simulation results are given from Fig. 3 to Fig. 5.

From Fig. 3 and Fig. 4, we can see that with the increase of the network size, the data packet delivery fraction is decreased and the average end-to-end delay of data packets is increased for all the evaluated protocols. However, in general, the QoS enhanced routing protocols outperform their non-QoS counterparts. This is due to the fact that QoS scheme can prevent the network from being heavily congested. Some flows may be suspended or even rejected to maintain the service quality of admitted flows. We also observe that using the mobile backbone network can further improve performance. The call admission delay of the QoS architecture is given in Fig. 5. We observe that due to the proactive nature of LANMAR routing, the admission delay is quite small. The MBN further reduce this delay a lot.

B. Scalability in Large Scale Networks with Mobility

In this experiment, we investigate the proposed QoS architecture in the large-scale ad hoc network under different mobility speeds. The network size is fixed as 1000 nodes. These nodes are uniformly distributed within a 5000m by 5000m field initially. When QoS-LANMAR routing is used, they are divided into 32 landmark groups. The mobile backbone network is the same as the previous experiment, except the transmission range of backbone radio is increased to 1000m. The offered load is 30 real time flows emulated using CBR connections with the bandwidth requirement of each CBR session being 80Kbps. Therefore, the total offered load is 2.4Mbps. The group mobility model is applied. We vary the mobility speed to analyze the impact of mobility on network performance. The results are presented in Fig. 6 and Fig. 7.

From Fig. 6, we observe that as we increase the mobility speed, the packet delivery ratio decreases for all the evaluated protocols. However, in general, the QoS enhanced routing protocols outperform their non-QoS counterparts. This is due to the fact that QoS scheme can prevent the network from experiencing heavy congestion, which reduces packet drops. Some flows may be suspended or even rejected to maintain the service quality of admitted flows. However, due to the large network size, the end-to-end paths are usually long (e.g. perhaps more than 10 hops), triggering many packet drops under mobility. The mobile

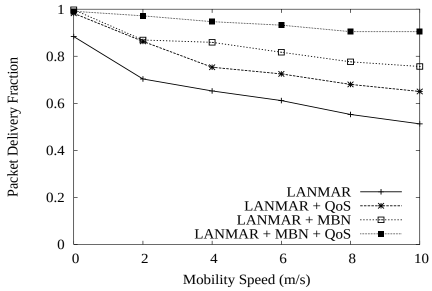


Fig. 6. Packet delivery ratio vs. mobility with 1k nodes.

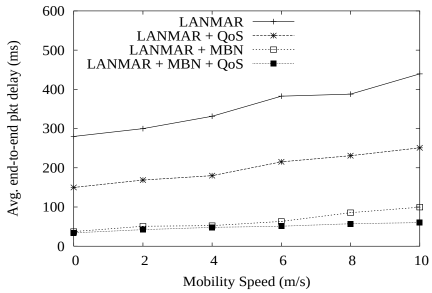


Fig. 7. Average end-to-end data packet delay vs. mobility with 1k nodes.

backbone network can effectively improve the performance of large-scale networks greatly, and thus help to maintain good delivery ratio under mobility.

Similar results are also observed for the average data packet end-to-end delay, as shown in Fig. 7. The average end-to-end delay is decreased significantly with the help of the mobile backbone network (MBN). The QoS scheme further helps reduce the packet delay. In terms of different mobility speed, we observe from Fig. 7 that the data packet delay of all four investigated protocols is not affected very significantly by mobility. This is due to the fact that LANMAR routing is a proactive routing protocol. Although mobility may increase the probability of path breaks, the periodical routing packet broadcast makes the route acquisition time minimal.

IX. Conclusion

In this paper, we proposed a scalable QoS architecture suitable for large scale mobile ad hoc networks. It is a DiffServ-like scheme targeting heterogeneous, wireless, ad hoc network as envisioned for the MOSAIC ATD. The major contribution of the proposed architecture is its scalability. Most of the work is pushed to the source nodes. Intermediate nodes only need to perform limited work without the need of any state information. With the help of the scalable LANMAR routing protocol, the proposed QoS scheme works efficiently in large-scale ad hoc network with thousands of nodes. Moreover, we also introduce the mobile backbone network (MBN) structure to further enhance network performance. Simulation results show that our proposed scheme has great potential to provide good QoS provisioning for future military wireless networks.

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